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ABSTRACT

With the passage of SCAQMD 1146.2, low NO_x regulations will be enforced for new water heaters and boilers from 22 to 585 kW starting January 1, 2000; less than two years away. This has given an added impetus to develop a burner capable of producing NO_x < 30 ppm and CO < 400 ppm without substantial manufacturing costs or complexity. Developed at the Berkeley Lab, the Weak-Swirl Burner (WSB) operates in the lean premixed combustion mode over a wide firing and equivalence ratio range. This work investigated scaling issues (e.g. swirl rates and stability limits) of the WSB when fired at higher rates useful to industry. Three test configurations which varied the ratio of furnace area to burner area were utilized to understand the effects of burner chamber coupling on emissions and stability. Preliminary tests from 12 to 18 kW of a WSB in a commercial heat exchanger were undertaken at LBNL, with further testing from 18 to 105 kW completed at UCI Combustion Laboratory in an octagonal enclosure. After scaling the small (5 cm diameter) to a 10 cm WSB, the larger burner was fired from 150 to 600 kW within a 1.2 MW furnace simulator at UCICL. Test results demonstrate that NO_x emissions (15 ppm at 3% O_2 at equivalence ratio $\phi = 0.80$) were invariant with firing rate and chamber/burner ratio. However, the data indicates that CO and UHC are dependent on system parameters, such that a minimum firing rate exists below which CO and UHC rise from lower limits of 25 ppm and 0 ppm respectively. Successful testing of the weak-swirl stabilization mechanism at firing rates of up 600 kW is a significant step in providing a low-NO_x burner technology to industry.

INTRODUCTION

Development of stationary heating and power generation equipment over the past few decades has been driven primarily by the increasingly strict rules adopted by California Air Quality Management Districts (AQMD). With over half of California's population, the South Coast AQMD (which includes all or portions of Los Angeles, Orange, Riverside and San Bernardino counties) and the Bay Area AQMD (the nine counties in the San Francisco Bay area) have been at the forefront in developing regulations to reduce pollution within their boundaries. In order to compete in this important market, emission regulations imposed on manufacturers and sellers of regulated equipment in these two regions are often used as benchmark standards for products sold nationwide.

Manufacturers of residential and small industrial combustion appliances have been pushed increasingly harder to lower emissions of oxides of nitrogen (NO_x, which includes nitrogen oxide, NO, nitrogen dioxide, NO_2, and nitrous oxide, N_2O) in a variety of applications. Examples of these regulations include: SCAQMD Rule 1111 limiting natural gas, fan-type residential central furnaces (< 51 kW) to NO_x < 40 nanograms/Joule of useful energy, SCAQMD Rule 1121 limiting natural gas residential hot water heaters (< 22 kW) to NO_x < 40 nanograms/Joule of useful energy, and SCAQMD Rule 1146.1 limiting small boilers, steam generators, and process heaters (585 to 1465 kW) to NO_x < 30 ppm corrected to 3% O_2, dry. With the passage SQAAMD 1146.2 on January 9, 1998, NO_x limits will be implemented for large water heaters and small boilers (22 to 585 kW) which were previously unregulated for NO_x emissions. Depending on the particular classification of the product, NO_x will be limited below 30 ppm for new products ranging from 117 to 585 kW, and below 55 ppm for products ranging from 22 to 585 kW. As these regulations will begin to take effect on January 1, 2000, manufacturers have less than two years to bring their new products into compliance with SQAAMD 1146.2 or risk being barred from that market[1-3].

Previous work at Ernest Orlando Lawrence Berkeley National Laboratory (LBNL) led to the development [4] of a novel burner which stabilizes a lean, premixed flame over a wide range of equivalence ratios, ϕ, and firing rates. It was termed the Weak-Swirl Burner (WSB) to distinguish it from current burners using higher swirl numbers ($S > 0.60$) which stabilize flames through the creation of recirculation zones. Laboratory tests proved that emission levels below 5 ppm NO_x could be obtained within a 15 kW commercial heat exchanger. To fire at the higher rates commonly found in commercial use, knowledge of scaling effects (e.g. swirl rates and stability limits) needs to be obtained through experimental results. Thus, a larger WSB was constructed (10 cm in diameter) which has potentially four times the firing rate of the smaller 5 cm WSB at the same reference velocity. Using two different furnaces at UC Irvine's Combustion Laboratory (UCICL), the WSBs were successfully fired at rates ranging from 18 kW to 106 kW for the 5 cm WSB, and from 146 kW to 585 kW for the 10 cm WSB. Emissions of NO_x, CO, UHC, CO_2, and O_2 for firing rates ($\phi = 0.80$) were recorded during this testing. The data obtained from the two geometries and three test configurations will allow a better understanding of how scaling the burner to larger sizes affects fundamental emission and stability characteristics of the WSB in applied situations.

BACKGROUND

The use of strong swirl for flame stabilization is common in gas turbines, dump combustors and industrial furnaces [5]. It is most effective for very high-speed flows as a means to control flame intensity, size and shape. Swirling motion is created either by tangential air injection, as in the designs of many cyclone combustion chambers, or by guide-vanes in an annular region surrounding a fuel rod. In either case, the significant function of swirl is to create a torroidal recirculation zone (TRZ). To promote the formation of a TRZ, a centered bluff body is often used in conjunction with a swirling annular flow. For non-premixed combustion, the TRZ promotes mixing of the fuel and air for more complete combustion, and stabilizes the flame by recirculating the hot combustion products. For premixed combustion, the TRZ generates a zone of hot combustion products that enables the flame to anchor itself at both the upstream and the downstream stagnation points. The mechanisms of TRZ flame stabilization have been the subject of numerous review papers [5, 6]

In Beer and Chigier [7], a swirl number for characterizing the swirl intensity is approximated as:

$$S \equiv \int_0^R UWr^2dr \Big/ R\int_0^R U^2rdr \tag{1}$$

When tangential injection is used, a geometric swirl number

$$S_g \equiv \frac{R_\theta * R * \pi}{A_\theta}\left(\frac{m_\theta}{m_t}\right)^2 \tag{2}$$

has been defined [8, 9] to allow for the calculation of swirl intensity without direct measurements of angular and axial velocities. The term “strong swirl” is applied to those burners with $S_g \geq 0.6$ as the onset of recirculation occurs at this level of swirl intensity.

Unlike the current, “strong swirl” burners, the WSB stabilizes the combustion zone by diverging the premixed reactants. Four swirl jets inject air tangentially (inclined 20^0 from horizontal) into the premixture upstream ($\ell/R = 2.8$) of the burner exit. As the swirl air is delivered to the flow periphery and does not dilute the core flow, ϕ is reported here without including the swirl air contribution. Adding swirl to an annular region and allowing the central core of the flow to remain undisturbed (i.e. no tangential velocity within the core), creates a radial mean pressure gradient that uniformly diverges the reactants. This configuration enables the flame to propagate upstream against the decelerating divergent flow, self-sustaining itself at the position where the local flow velocity equals the flame speed. Since the WSB stabilizes a flame without using recirculation as the means of stabilization, S_g is below 0.6 and the term “weak-swirl” is used to describe the burner.

APPARATUS AND DIAGNOSTICS

Schematics of the WSBs and the three test chambers are shown in Figures 1-3. When utilizing the LBNL water heater simulator, the 5 cm WSB sits atop a 2” pipe cross (Figure 1a). The interior of the cross is filled with marbles to help break down large flowfield disturbances as the homogeneous premixture enters from the side. Two perforated screens help to promote flow uniformity, as well as adding moderate turbulence (6-8%) to the flow. The smaller burner has an exit radius R = 26.4 mm, swirl injector radius R_θ = 1.6 mm, and an exit tube length of ℓ = 70 mm. The hot water simulator at LBNL has a commercial heat exchanger taken from a Telstar 50,000 Btu/hr spa heater (Figure 1b). It is rectangular in shape (15 cm deep, 22 cm wide, 24 cm tall), with a fin-and-tube heat exchanger 4 cm below the top. Emission samples were taken 50 cm downstream of the heat exchanger in a 10 cm (diameter) exhaust flue. In conjunction with the 5 cm WSB, the LBNL water heater simulator has a chamber area / burner area ratio A_c / A_b = 15. More details of this configuration can be found in [10].

Figure 2a shows the 5 cm WSB when used in the UCICL octagonal enclosure. Natural gas is entrained through a venturi upstream of the swirler section and is mixed with the reactant air within the premixing zone. Once downstream of the two perforated plates, the burner is identical to the 5 cm WSB described above. With the burner firing vertically into the enclosure, emissions are sampled 150 cm above the enclosure floor. The octagonal furnace at UCICL measures 60 cm across and 175 cm in height, consisting of eight high temperature windows (25 cm by 30 cm) on the bottom third of the enclosure, and eight water cooled panels (25 cm by 60 cm) above the windows (Figure 2b). The area ratio A_c / A_b = 142 is an order of magnitude larger than the LBNL test station.

The larger burner with an exit radius R = 50.8 mm is designed to keep the non-dimensional parameters of R_θ/R and ℓ/R similar to the smaller 5 cm WSB, with a swirl injector radius R_θ = 3.2 mm, and an exit tube length of ℓ = 140 mm. As is the case with the 5 cm WSB, the exit tube is tapered to 45^0 to help prevent the formation of a recirculation zone above the burner rim. 80 cm upstream of the exit rim, natural gas is injected in the upstream direction against the incoming reactant air. The two perforated plates enhance the mixing of the fuel and air. Immediately upstream of the swirler section, a 7 cm thick section of honeycomb material is used to destroy large scale turbulence structures created in the premixing zone (Figure 3a). The interior dimensions of the large furnace simulator at UCICL are 240 cm square by 300 cm long (A_c / A_b = 733) with the exhaust exiting from the wall opposite the horizontally fired burner. Viewports give visual access from the front, rear, and side of the furnace. Figure 3a and 3b show schematics of both the 10 cm WSB and the UCICL furnace simulator. More details of the UCICL test chambers can be found in [11, 12].

TEST RESULTS

As the 10 cm WSB has four times the area of the 5 cm WSB, firing rates will be four times higher for the same reference velocity (at identical ϕ). Figure 4 shows the results from the experimental runs at UCICL in both the octagonal enclosure (5 cm WSB) and the furnace simulator (10 cm WSB) with ϕ held constant at 0.8. For the 5 cm WSB, operating conditions ranged from 18 kW to 106 kW (2.7 to 16.6 m/s) while the 10 cm WSB fired at rates from 146 kW to 585 kW (6.2 to 24.8 m/s). The maximum firing rates shown here are not the highest rates attainable. In both cases, the maximum firing rate was limited by peripheral components; i.e. cooling capacity of the octagonal enclosure for the 5 cm WSB and the amount/pressure of swirl air available for the 10 cm WSB. There is no indication that the burners could not be fired at higher rates given sufficient ancillary support. Definitive lower limits on the firing range were not explored as earlier experiments at LBNL determined a lower limit for the reference velocity U_{ref} of approximately twice the flame speed to avoid flashback conditions. Testing the 5 cm WSB in the octagonal enclosure established the stable operating range from $S_g = 0.02 - 0.04$ for $U_{ref} = 3$ to 17 m/s. When the same S_g (≈ 0.04) was applied to the 10 cm WSB for our first test at ≈ 12 m/s, flame blow-off was immediate. Additional tests established the operating regime for the 10 cm WSB at a higher $S_g \approx 0.08$ as shown in Figure 4. Two trends appear; first, stable operation of the 10 cm WSB requires S_g to be 2 - 2.5 times greater than for the 5 cm WSB at similar velocities, where a doubling of S_g requires an increase of 66% more swirl air. The second trend which is evident is that unlike the 5 cm WSB where S_g increases with U_{ref}, S_g appears level for the 10 cm WSB over a wide range of reference velocities.

As noted earlier, regulations are driving the manufacturers to decrease pollutants, particularly NO_x, emitted by combustion equipment. Demonstrating the feasibility of the WSB to achieve firing rates up to 600 kW is an important first step. However, it is the WSB's emission characteristics that are of primary interest to industry. Previous research at LBNL demonstrated low levels of NO_x and CO being emitted by the 5 cm WSB in a water heater simulator. Figures 5 and 6 show NO_x and CO respectively, over equivalence ratios of $0.70 \leq \phi \leq 0.90$ while firing at 12 to 18 kW; -/+ 20% of the heat exchanger's rated capacity of 15 kW. As expected, NO_x primarily depends on ϕ, with levels increasing from 5 ppm at $\phi = 0.70$, to ≈ 15 ppm at $\phi \approx 0.80$, and ≈ 35 ppm at $\phi = 0.90$. Figure 5 also shows that although the firing rate is increased by 50% from a minimum firing rate of 12 kW, there is only a insignificant change in NO_x with the increasing input power. This dependence on ϕ is caused by the higher flame temperatures associated with ϕ as stoichiometry is approached. As there are negligible amounts of nitrogen in natural gas, the generation of NO_x in premixed flames is overwhelmingly dependent on the oxidation of atmospheric nitrogen at high temperatures. Described by the Zeldovich mechanism, the production of NO_x increases exponentially with temperature, and thus NO_x is not directly effected by firing rate. This is not the case with CO, where Figure 6 clearly shows a substantial decrease in CO as the firing rate increases to 18 kW. Reductions of > 60% are seen for $\phi = 0.70$ to 0.90. From a high of 1350 ppm at $\phi = 0.70$ when firing at 12 kW, to a low of 17 ppm at $\phi = 0.90$ and 15 kW, it has been demonstrated that CO emissions can be greatly altered while still achieving the low NO_x emissions seen Figure 5.

By changing the chamber/burner area ratio, the dynamic coupling of the burner chamber interaction can be readily investigated. Using $\phi = 0.80$ as a standard condition, the effects of burner chamber coupling are compared for the 5 cm and for the 10 cm

WSBs. The 5 cm WSB was fired within the UCICL octagonal combustion chamber where the A_c / A_b = 142, roughly an order of magnitude greater than the area ratio found in the LBNL water heater simulator. The 10 cm WSB was fired into the UCICL furnace simulator with a ratio of A_c / A_b = 733. This is a 50-fold increase from the A_c / A_b = 15 found in the LNBL experimental setup. Figures 7, 8, and 9 show the results of these tests for NO_x, CO, and UHC. The two x-axis scales using firing rates of the 5 and 10 cm WSB are equivalent to the same U_{ref} (from 0 to 25.5 m/s for both).

As seen in Figure 7, no dependence of NO_x with firing rate (encompassing a 5 to 1 turndown ratio) is exhibited. Nor is there any difference associated with the three different chamber/burner area ratios. Thus the level of NO_x emissions is a local effect within the combustion zone, and does not depend on overall system effects such as chamber size and firing rate. NO_x levels consistently stay within a few ppm of 15 ppm, with even the highest reading of 21 ppm well below the strict regulations imposed by SCAQMD 1146.2.

Figure 8 however shows the importance of firing the WSB at specific minimal input rates in order to achieve optimal CO levels. Plotted on a logarithmic scale to display the full range of CO emission levels, it is seen that identical firing rates can produce drastic changes in CO due to burner chamber coupling. The 5 cm WSB firing at 18 kW in the LBNL simulator (A_c / A_b = 15) achieved CO = 50 ppm while the same firing rate in the octagonal enclosure (A_c / A_b = 142) produced significantly higher emissions with CO = 2500 ppm. As firing rates increase within each of the three enclosures, CO levels drop substantially. When the WSB is fired above a minimal input rate of ≈ 65 and 400 kW in the octagonal enclosure and in the furnace simulator, CO emissions attain a constant level of 25 ppm. Extrapolating from the three data points available for the LBNL water heater, it appears that a minimum firing rate of 25 kW is sufficient to reduce CO to 25 ppm. It should be noted that the dashed lines in Figure 8 are there to guide the eye, and are not intended to be trend lines fitting the data points.

In Figure 9, the data obtained for unburned hydrocarbons also illustrates the effect of burner chamber coupling. The small WSB firing into UCICL octagonal enclosure shows how a small change in firing rate can have a major impact on emission levels. By doubling the input power from 18 kW to 36 kW, UHC production is decreased from 2800 ppm to 60 ppm (average). Despite the large data scatter (e.g. UHC = 35 and 85 ppm at 36 kW) and fluctuations (e.g. 0 ppm at 210 kW, rising to 15 ppm at 300 kW before dropping down to 0 ppm again), the general trend of the data set indicates that for firing rates above 75 and 300 kW (similar U_{ref} of ≈ 12 m/s), UHC emissions are essentially 0 ppm.

DISCUSSION

Testing of the 10 cm WSB at UCICL was designed to study if the WSB could be scaled to firing rates of commercial interest while still achieving the same low emission levels as those measured in a smaller burner. By doubling the burner radius from 5 cm to 10 cm, four times the firing rate is achieved for the same reference velocity. Our design had kept the non-dimensional parameters of R_θ/R, ℓ/R, and S_g similar. The intent was to show that the stability regime (as defined by S_g) would be similar for the two burners. As Figure 4 displayed, that was not the case as the stability regime is twice as high for the 10 cm WSB as for the 5 cm WSB. This indicates that the amount of divergence needed for flame stabilization in the large burner was not accomplished even though the conditions (i.e. U_{ref} and S_g) were similar to those found for a smaller burner in a stable operating mode. This non-linearity may be caused by burner chamber coupling, buoyancy effects, or flame speed differences due to varying levels of turbulence.

Unlike NO_x emissions which are constant at 15 ppm for an equivalence ratio of 0.80, CO and UHC levels are more dependent on system variables such as firing rate and chamber size. Figures 6, 8 and 9 all demonstrate how slight changes in firing rates can produce significant variations in both CO and UHC. Burner chamber coupling, as displayed by the chamber/burner area ratio in Figure 8, has a significant role in the production of CO. Once specific minimal input powers are achieved (dependent on chamber size), CO emission levels were essentially uniform at 25 ppm and UHC remained constant at 0 ppm for the tests completed at UCICL.

SUMMARY AND CONCLUSIONS

Our tests of a large weak-swirl burner were successful in proving that the weak-swirl stabilization mechanism can be scaled to higher firing rates while the flame's emissions remain well below the limits set by the strictest air pollution regulations in the country; those adopted by SCAQMD. Also it was found that NO_x did not vary with system parameters and remained constant at 15 ppm for $\phi = 0.80$ over a wide range of firing rates. CO and UHC were dependent on burner chamber coupling with minimal levels of 25 and 0 ppm achievable for optimal firing conditions. The stability regime as defined by the geometric swirl number S_g did not scale linearly between the 5 cm and 10 cm WSB, even though non-dimensional parameters and reference velocities were similar. As the WSB stabilizes the flame through flow divergence, the scaling of S_g with divergence rates needs to be investigated. An alternative swirl number more applicable to the WSB operation may need to be developed to better represent the fundamental stabilization mechanism of the WSB. This is because the tangential velocity in our configuration is only present on the periphery of the reactant flow and is not distributed throughout the flowfield as is the case in other swirl burners. These test results show that using the WSB in commercial applications is feasible and it will generate NO_x emissions well below new regulatory limits.

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NOMENCLATURE

ϕ = equivalence ratio

ℓ = length of exit tube = 70 or 140 mm

A_c / A_b = chamber cross-sectional area/burner cross-sectional area = 15, 142, and 733

R = radius of exit tube = 26.4 or 50.8 mm

R_θ = radius of air injectors = 1.6 or 3.2 mm

S_g = geometric swirl intensity $\equiv \frac{R_\theta * R * \pi}{A_\theta}(\frac{m_\theta}{m_t})^2$

m_θ = tangential mass flow = cos (20^0) * mass of swirl air

m_t = total mass flow

A_θ = total area of injectors

U_∞ = reference flow velocity $\equiv (\dot{v}_a + \dot{v}_f)/(\pi R^2)$

$\dot{v}_a$ = volume of reactant air

$\dot{v}_f$ = volume of fuel

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